Collaborative Unmanned Systems for Maritime and Port Security Operations

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Introduction

This paper deals with some recent work ongoing at NPS, which attempts to show the utility of networked distributed vehicles for Maritime Interdiction, Riverine Operations, and related missions. We believe that these systems will be essential for dealing with the challenges in confronting these important National future needs.

Maritime Domain Awarenesss

The recent Presidential Directive for Maritime Security includes needs for *Maritime Domain Awareness*, MDA [1]. While this is a large subject in general, there are certain needs for new technology that imply requirements for further development of Sensors and Platforms. More specifically, the following are listed:

- Improve WMD portable and standoff detection capabilities by integrating parallel efforts,
- Bolster coastal surveillance through sensor packages, which may be shore-based, airborne, or deployed on buoys and offshore platforms, as well as shore-based and elevated integrated radar and camera (night, infrared, day) systems.
- Strengthen open ocean surveillance and reconnaissance capabilities to better verify AIS data, identify vessels not previously known, and provide additional information on crew activity, and cargo loading. Leverage commercial assets that can correlate vessel position information.
- Integrate and network existing platforms to enhance shared situational awareness.
- Ensure that all future acquisitions are integrated and networked with appropriate sensor technologies.
- Improve acoustic contact identification and data management [1].

Additionally, new missions have been defined Figure(1).

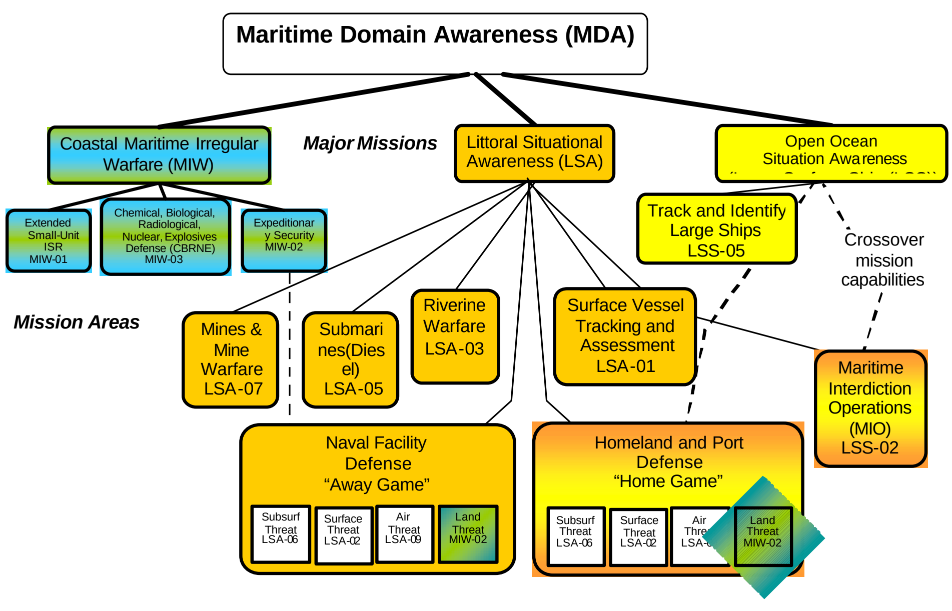

Figure 1 Taken from [2]

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As shown in Figure (1), Maritime Interdiction (MIO) , and Riverine Warfare as well as Mine warfare, are now seen as missions pertaining to MDA. Also Port and Harbor Security are listed as both Home Port as well as Navy Port Facilities needing monitoring and surveillance.

Distributed Autonomous Systems

Distribute Autonomous Systems fill the need for continual surveillance both above and below the waterline. Aircraft in the form of UAVs have large endurance, coverage, and can be stealthy. Surface vessels, USVs have large endurance and reasonable coverage. Underwater UUVs are covert. By networking these assets, we get the best of all configurations to accomplish the intended missions.

Table 1 Fuzzy Score for Capability Ratings Suggested

	Durability	Coverage	Duration	Stealth	Station Keeping
AUV	7	4	5	10	7
UAV	5	10	2	7	5
USV	9	6	10	2	10
UGS	8	2	6	7	10

In principle, networked vehicles can provide wide area coverage, send commands from a control station, self task, provide situational awareness to each other, and video and sensory data to a command center.

The work of the Center for AUV Research at NPS is focused on the development of tactics and technology in support of these ideas and attempts to provide experimental validation of concepts through field experimental programs.

Field Experimentation Programs

We consider two related mission for experimentation with networked operations with collaborating vehicles. Firstly, we consider the video collection capability of a networked UAV to provide target cueing to a surface vessel USV, which then will use the information to perform target inspection. The UAV normally carries a camera which is pointed at the USV and maintains lock on the USV directing its path using the vision-based guidance methodology developed by Kaminer et. al. in [3]. In our experiments first at Camp Roberts, CA and then at Pamana City FL, at AUVFEST 2007, we have used both the Scan Eagle and the SIG Rascal aircraft to provide such video cueing interfaces. NPS has modified both platforms to use ITT Mesh [4] based radio modems, operating at 2.4 GHz. as the communications basis. The Scan Eagle UAV, is catapult launched and recovered to a taught vertical wire, and has been modified to carry the radio modem package with a 1 watt amplifier. The USV Sea Fox was developed for Navy Missions as a radio controlled boat, but has now been modified to accept commands from the radio network. An ITT Mesh card radio modem has been installed and developed in a LINUX based PC-104 secondary controller running NPS developed GNC and data logging software, Figure(2).

Figure 2, NPS Scan Eagle and Rascal UAVs and the Sea Fox USV.

Scan Eagle / Sea Fox Collaborative Operations

While the recent focus has been on Scan Eagle / Sea Fox operations, preliminary results were obtained at Camp Roberts with Scan Eagle communicating to a ground station. The normal ground station is coupled to a high gain tracking antenna which uses airplane position to set a pan and tilt angle – sufficient for good tracking when the Airplane speed is relatively slow (70 knots). Figure 3 shows the high gain 40dBi antenna (2deg beam width) which has been modified recently to accept not only command and control signals on a 960MHz radio channel with a secondary analog video channel receiver at 2.3 GHz., but to also receive the 2.4 GHz. Mesh network digital signal. These signals are received at the Scan Eagle ground station which is used as the primary command and control center.

Sea Fox, Figure (5), has been outfitted with a Mesh network card in a PC 104 secondary controller linked to the primary original autopilot system and the video server that transmits video from gyro stabilized cameras either through a separate radio link, or more recently through the Mesh network link.

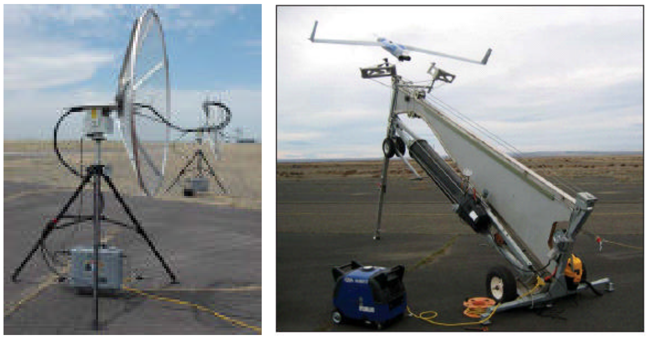

Figure 3 Scan Eagle Tracking antenna (left) and pneumatic launcher (right)

Figure 4 Scan Eagle Sky Hook Recovery

Figure 5 Sea Fox at AUVFEST 07

Network Data Rates / Range

We are still continuing our study of data rates and range for network performance evaluation, but preliminary results Table II, have indicated that throughput of about 400Kbits per sec out to nearly 20km is feasible. This data was obtained at Camp Roberts over land with a moving ground vehicle and Scan Eagle at about 1000m AGL. Much depends on terrain and aircraft attitude, antenna beam patterns, gain, and altitude. It also appears that network loading becomes and issue and when we had video transmitting through the network and 12 nodes active at AUVFEST 07, the network basically crashed most of the time.

Table II Camp Roberts Data, 07

Total Link Distance [km]	Data Rate [kbps]
21.8	481.9
18.5	318.1
18.0	92.8
17.1	139.3
15.8	434.6
16.3	94.5
17.2	243.8
18.2	358.6
19.2	N/A

During the AUVFEST 07 exercise, we did find a period when the network was available to successfully command Sea Fox to begin a Riverine Mission under autonomous control, initiated by a command through the Scan Eagle ground station location while the Scan Eagle camera was commanded to focus closely on Sea Fox. At the same time, the Rascal UAV was circling above SeaFox maintaining its camera on the SeaFox. This experiment illustrated “bent Pipe” communications to Sea Fox from remote locations, initiation of autonomous mission via aircraft data relay, and maintaining video surveillance of Sea Fox from the air, independently of UAV flight path.

Maritime Interdiction Operations

For MIO operations we have been developing secondary controllers for Sea Fox and updating the primary autopilot behavior. We have developed an autopilot that responds to heading commands from a guidance function that develops desired paths through the use of artificial potential fields.

The heading commands are then converted into rudder commands using a PD controller with turn rate estimation from compass data. While there is no side slip feedback, the control is not as robust as it could be, but precise control at the low level was not the objective at this point in time.

Rudder and engine commands were sent by serial data link running at 8 Hz. to the primary control system that was developed originally for use with a radio manual control. This is still active as a means of emergency override when needed. As shown in Figure 9, the manual commands sent through the MRoss radio, always have precedence through the serial splitter, over commands from the PC-104 secondary autonomous controller.

Sea Fox Modeling and Secondary Controller Development

The SeaFox autopilot control is modeled by a first order lag with an integrator for the response from thrust angle to heading. The gain is speed dependent, so is the time constant and some maneuvering circles were made for various thrust angle settings and speeds to provide a basis

for identification of the gain and time constant. By matching the transition between clockwise and anticlockwise turns, a rough set of gains and time constants were found and used as the basis for the control functions. For Sea Fox running at 5 knots, the gain was 0.75 deg/deg and a time constant of 2 seconds was used, Figure (8). This also included a rate limit on thrust angle change of 0.2 rad/sec with an angle limit of 0.3 rad.

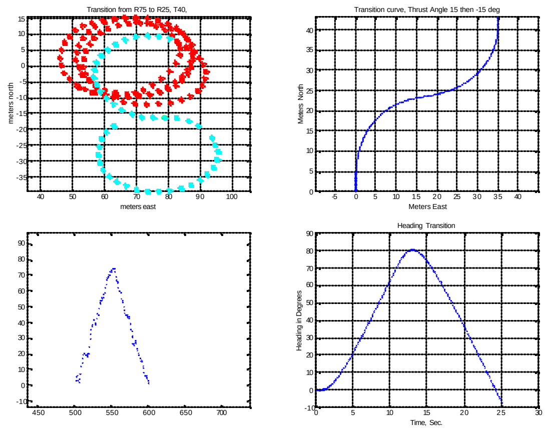

Figure 8 Paths and Heading During Transition Curve vs Time (Lower Left is Time *5). Used to establish gain and time lags.

Hardware modifications made to allow for automation and network control are shown in Figure 9. The red blocks are basic equipment for manual radio control, while the blue blocks are added for network control. Note that manual control is still necessary for emergency shut down and override, accomplished with the serial switch having the manual control line always preferred if active.

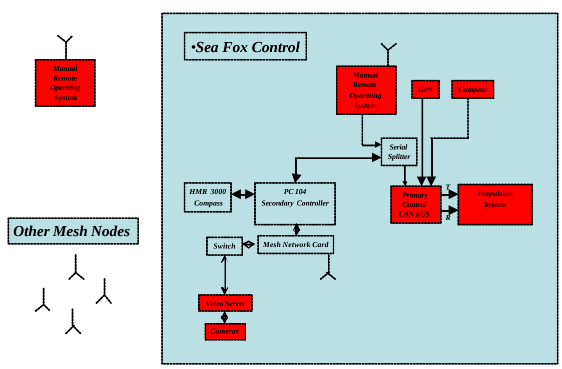

Figure 9 Sea Fox Secondary Controller for Mesh Network Control

Potential Function Guidance Laws

Sea Fox guidance is accomplished using Potential Field methods [5-11]. The motion is a kinematic model involving rate of change of Northerly and Easterly position as related to a single control variable in the commanded heading. The vehicle speed is assumed to be constant at some predefined level for each mission leg. It follows from our previous work that the commanded heading to a heading controller is given by

$$\psi_{com} = a\tan(-V'_Y, -V'_X)$$

in which V'_Y and V'_X are the East and North components of the total potential field at a point on the planned path which the Sea Fox is tracking.

Track Following

For a mission that is most commonly described by a sequence of tracks between way points, the potential field is

$$V_t = b(L - s);$$
$$V_n = 0.5ke^2;$$

composed of an along track and a cross track potential, gradients of which are rotated to the north / east grid. b and k are adjustable parameters and e and s are, respectively, cross track error and distance to go as projected along the track.

Inspection /Loiter /Obstacle Avoidance State Machine

The canonical state machine for mission control for a MIO Operation includes, 3 states; Obstacle Avoidance, Loiter and Inspect. It is assumed that while the inspection is ongoing, we assume the USV will not be concerned with O/A so the diagram is given in Figure 10.

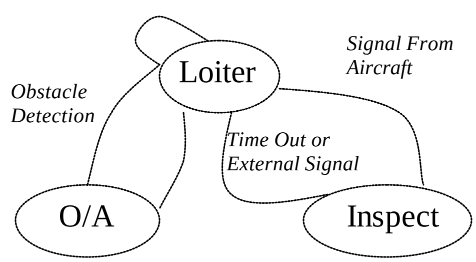

Figure 10 Canonical State Machine for MIO

In order to intercept and inspect a slowly moving target, we define a boundary function in terms of an ellipse for which the center point is moving with a speed and heading. The ellipse is in line with the heading vector. Naturally, making the major and minor axes equal, the boundary function is a circle. We define normal and tangential potentials as follows;

$$
\begin{aligned}
&V = V_n + V_t;\\
&V_n = s\,(x,y,t)^2\\
&\textit{Ellipse Moving Boundary:}\\
&s = (\tilde{x}/a^2 + \tilde{y}/b^2 - 1);
\end{aligned}
$$

$$
\begin{bmatrix}\tilde{x}\\ \tilde{y}\end{bmatrix} = \begin{bmatrix} cos(y_s) & sin(y_s)\\ -sin(y_s) & cos(y_s)\end{bmatrix}\begin{bmatrix}(X(t)-X_0(t))\\ (Y(t)-Y_0(t))\end{bmatrix}
$$

$$
V_n^{'} = \begin{bmatrix}2s\,s_X^{'}\\ 2s\,s_Y^{'}\end{bmatrix};\ \begin{bmatrix} s_X^{'} = 2(\tilde{x}\cos^2(y_s)/a^2 + \tilde{x}\sin^2(y_s)/b^2)\\ s_X^{'} = 2(\tilde{y}\sin^2(y_s)/a^2 + \tilde{y}\cos^2(y_s)/b^2)\end{bmatrix}
$$

$$
V_t^{'} = \begin{bmatrix}-ct_x\\ -ct_y\end{bmatrix};\ \begin{bmatrix} t_x = (\tilde{y}/b^2)/\sqrt{(\tilde{x}/a^2)^2 + (\tilde{y}/b^2)^2}\\ t_y = (-\tilde{x}/a^2)/\sqrt{(\tilde{x}/a^2)^2 + (\tilde{y}/b^2)^2}\end{bmatrix}
$$

a,b,c *are constants*

Thus, when the inspect state is entered, the new heading command is derived from

$$
\begin{aligned}
&y_{com} = a\tan 2(-V_Y^{'}, -V_X^{'})\\
&with\\
&V_X^{'} = 2s\,s_X^{'} - ct_x;\\
&V_X^{'} = 2s\,s_Y^{'} - ct_y;
\end{aligned}
$$

Experimental Results

These guidance laws have been developed in Matlab simulations and by experimental validation during AUVFEST and subsequent TNT exercises at Camp Roberts. In Figure 11, we show the Sea Fox path results from a mission that has it in a loiter pattern followed by a command to inspect a target with a circular motion inside the loiter box (a), and (b) a target outside the loiter box. After a prescribed time, the Sea Fox returns to its loiter box.

Clearly, the guidance laws are followed. The precision of curved path tracking could be improved with use of a higher sampling rate autopilot, and continued work for control at higher speeds is required. These experiments with moving ships are being developed in San Francisco bay through organized MIO operations.

Simulation Results

Simulations of MIO inspection tracks with a slowly moving vessel are given in Figure 12 which shows Sea Fox path

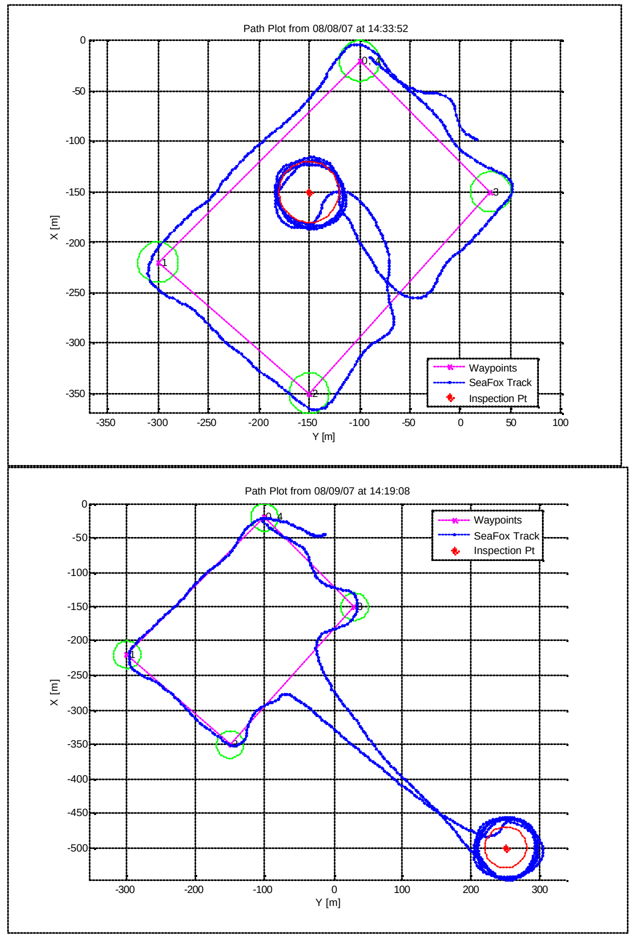

Figure 11 (a) above, (b) lower. Path response of Sea Fox , Camp Roberts, TNT exercise in Lake San Antonio, Aug 07.

generated by the APF guidance law to surround the target ship as it moves. In this simulation, the APF functions are used to develop a curved path that the vehicle tracks with a curved path tracking law similar to that described in [12].

Conclusions

Maritime Domain Awareness requires new tools including the use of Autonomous Systems with Coordinated Autonomy for situational awareness, maritime interdiction, tracking and inspection. The use of aerial UAVs to provide video tracking support and subsequent target information to USV ships has been studied. Both in simulation and in experiment, our results are showing that this type of networked autonomous system of systems is both appropriate and possible. Many questions are still to be resolved including network performance for field trials, automation of assets that are proprietary where primary controllers cannot be modified, and integration of video tracking and control capabilities across platforms, and the network.

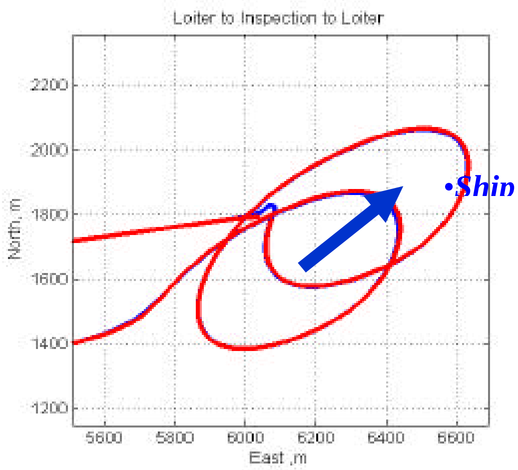

Figure 12, Simulated Target Ship Inspection Track Generation and Following.

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